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Model of an intelligent energy harvesting system from microbial fuel cells in wastewater treatment process

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Article Info	ABSTRACT
	This paper presents a model of an intelligent energy harvesting system from microbial fuel cells (MFCs) in the wastewater treatment process. The model consists of two direct current (DC/DC) converters connected in a cascade. One DC/DC converter is used to capture energy from MFC and store it in a supercapacitor. The other DC/DC converter is responsible for increasing the low output voltage to a higher voltage level. In the paper, the MFC is modeled by a DC voltage source instead of a real MFC that contains wastewater inside it. The experimental results demonstrate that the model of an intelligent energy harvesting system can increase the low output voltage of MFC up to 3.3 V and achieve intermittent output power at a high level that can use in practice.

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1. INTRODUCTION

The microbial fuel cell (MFC) is one of the renewable energy sources. The MFC uses exoelectrogenic microorganisms in wastewater or sediment to convert the chemical energy stored in biodegradable substances to direct electricity [1]-[4]. However, the MFC's voltage and power are lower than that of other renewable energy sources such as wind energy, solar energy, biomass energy because of its thermodynamic limitation. Typically, the output voltage of MFC is about 0.7–0.8 V, and the output power is 1000–2000 mW/m^2 [5]. Thus, the MFC cannot be used in practical applications that almost require the lowest output voltage of about 3.3 V. Moreover, the higher power production cannot be easily achieved by increasing the sizing of MFC or connecting MFCs in series or parallel because of its nonlinear nature characteristics [6], [7]. Consequently, an energy harvesting system from MFC is required.

Many energy harvesting technologies have been researched in recent years, such as capacitors, charge pumps, and boost converters. In [8], the authors use an electronic circuit containing two sets of multiple capacitors that are alternately charged and discharged. The capacitors are charged in parallel by MFCs but linked in series while discharging to the electrical load. The output voltage of this method is up to 2.5 V with four capacitors. However, the capacitor can be controlled in another way [9]. After charging to a determined potential, the ultracapacitor is disconnected from MFC and discharged through a resistor. This energy harvesting technology is called an intermittent energy harvesting system. In [10], a bioelectrochemical system

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that can be operated in both modes, such as microbial fuel cell and microbial electrolysis cell, has been introduced. The capacitor is first charged by MFC. Then, the capacitor discharges its energy to the system, switching into microbial electrolysis cell mode. These alternate charging and discharging modes helped the system produce a 22-32% higher average current than an intermittent mode. The energy harvesting systems used capacitor have a low output voltage because the maximum voltage is only equal to the MFC's open-circuit voltage.

To overcome this disadvantage, a charge pump technology has been applied to the MFC [11]-[14]. The charge pump is based on the supercapacitor or ultracapacitor. First, the charge pump charges the capacitor. Then, the capacitor is connected in different ways to achieve the desired voltage level. However, the charge pump's output voltage is not high enough for the electrical loads that require at least 3.3 V. Thus, a direct current (DC/DC) boost converter is necessary to increase the output voltage to a higher value [15], [16]. A. Meehan *et.al*. [15], a charge pump is used to charge the supercapacitor voltage up to 1.8 V. Then, the DC/DC boost converter receives a sufficient voltage and energy from the supercapacitor and therefore starts up, thus providing 3.3 V voltage to the load. A high-efficiency DC/DC boost converter is also proposed to interface a miniaturized 50 μL MFC [16]. At 0.9 V, the converter has a peak efficiency of 85% with 9 μW loads. Besides, the energy harvesting from MFC cannot achieve the peak energy at all times because the internal resistance and power density curve of MFC varies with the changes of microbial activities and operational parameters. To improve this situation, the maximum power point tracking (MPPT) techniques [17]-[19] have been applied for the MFC such as perturb and observe (P&O) method, gradient method, multiunit optimization method. In these cases, the MPPT is implemented to control the duty cycle of the boost converter to capture the maximum power point. The charge pump and DC/DC boost converter system have a complex structure and control. Moreover, the DC/DC boost converter with a high duty cycle often causes instability in the output voltage.

Thus, this paper presents a model of an intelligent energy harvesting system from MFCs in a wastewater treatment process with simple structure and control using two DC/DC converters connected in a cascade. The organization of this paper is as follows. Section 2 presents the concepts of MFC, the DC/DC boost converter, and the proposed energy harvesting system. The experimental results and discussion are shown in Section 3. Section 4 is the conclusion.

2.   RESEARCH METHOD
2.1. Microbial fuel cell
Generally, an MFC consists of the anode and cathode chambers, physically separated by a proton exchange membrane (PEM) [20]. The MFC uses bacteria as catalysts to oxidize organic substrates and generate electrons and protons. Then, the electrons are transposed to an anode surface, and the protons move through the proton exchange membrane toward a cathode. If the anode and cathode are connected by an external circuit, the produced electrons will flow through this circuit to the cathode. In the cathode chamber, the protons and electrons are reacted along with a parallel reduction of oxygen to water. An example of the reaction at the anode and cathode chambers is illustrated as (1) and (2).

$$C_2H_4O_2 + 2H_2O \rightarrow 2CO_2 + 8e^- + 8H^+ \tag{1}$$

$$2O_2 + 8H^+ + 8e^- \rightarrow 4H_2O \tag{2}$$

In the wastewater treatment system, the MFC generates electricity at the same time with chemical oxygen demand (COD) and biochemical oxygen demand (BOD) removals [2]. To continually generate electricity from organic matter in water, an MFC reactor must have a large surface area for biofilm formation and a high void volume. The output voltage of MFC in the wastewater treatment system is often low. For wastewater containing up to 220 mg/L of COD and a pH ranging from 7.3 to 7.6, the voltage across the circuit connected to a 465 Ω resistor is about 0.32 V, producing up to 9 mW/m^2 of power based on anode surface area (hydraulic retention time = 12 h; air flow rate = 5.5 L/min) [2]. In an artificial wastewater treatment system, the upflow MFC is fed at a loading rate of 1.0 g COD/L/day and a flow rate of 0.36 ml/min during the start of operation [21]. The open-circuit potential reached 0.75 V on day 3 of the operational period. When the upflow MFC is connected by a 66 Ω resistor, the maximum power density is about 170 mW/m^2 occurred 0.33 V.

In this paper, the MFC is modeled by a DC voltage source and a resistor connected in series, as shown in Figure 1. The average voltage of MFC is about 0.33 V. The voltage and internal resistance of MFC may be nonlinear quantities because they depend on the bacterial activities, environmental conditions, external loads. From Figure 1, we have:

$$v_{MFC} = V_{int} - i_{MFC}.R_{int} \tag{3}$$

where,
v_{MFC} : is the output voltage of MFC,
V_{int} : is the internal voltage of MFC,
i_{MFC} : is the output current of MFC or load current,
R_{int} : is theinternal resistor of MFC.
If the load current increases, the MFC voltage will be decreased and vice versa. As the load current is zero, the bacterial community will be restored. Thus, the MFC voltage increases gradually up to its open voltage.

2.2. DC/DC boost converter

A DC/DC boost converter is a power electronic device that is used to step up a DC voltage [22]. This converter is often applied to low and medium power systems (such as the wind power system and the solar power system) or very small power systems (such as the electronic circuits). Specifically, the structure of the DC/DC boost converter is shown in Figure 2. It consists of an inductor, capacitor, diode, and metal–oxide–semiconductor field-effect transistor (MOSFET). The waveforms for voltages and currents are shown in Figure 3 for the continuous load current. The operation of the DC/DC boost converter can be divided into two modes as follows;

- Mode 1: MOSFET Q_1 is switched on at $t = 0$. The input current flows through inductor L and MOSFET Q_1. The inductor L charges energy, and the current rises gradually (Figure 3 (a)). The output voltage, v_o, is equal to the capacitor voltage, v_C, ($v_o = v_C$) as shown in Figure 3 (b).
- Mode 2: MOSFET Q_1 is switched off at $t = t_1$. The current which was flowing through the MOSFET Q_1 would now flow through L, C, load, and diode D. The inductor current falls until MOSFET Q_1 is turned on again in the next cycle. The energy stored in inductor L is transferred to the electrical load. The output voltage, v_o, is equal to $V_i + v_L$ (Figure 3 (b)). Figure 3 (c) shows the output current of the DC/DC boost converter.
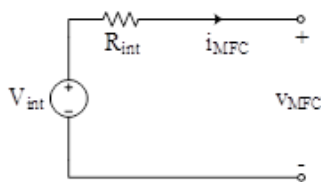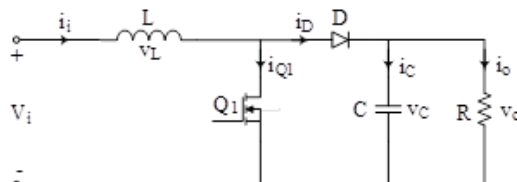

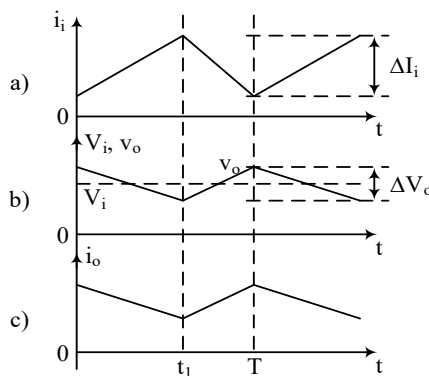Figure 1. Equivalent circuit of MFC   Figure 2. DC/DC boost converter

Figure 3. Waveforms; (a) input current, (b) output voltage, and (c) output current

The average output voltage of the DC/DC boost converter is calculated as:

$$V_o = \frac{V_i}{1-d} \tag{4}$$

where,
V_i : is the input voltage of the DC/DC boost converter,
V_o : is the average output voltage of the DC/DC boost converter,
d : is the duty cycle of the DC/DC boost converter. It is determined by

$$d = \frac{t_{on}}{t_{on} + t_{off}} \tag{5}$$

t_{on} : is the on time of MOSFET ($t_{on} = t_1 = dT$),
t_{off} : is the off time of MOSFET ($t_{off} = (1 - d)T$),
T : is the switching period of MOSFET.

      The output voltage of the DC/DC boost converter is very sensitive to changes in the duty cycle. The relationship between the duty cycle and the output voltage of the DC/DC boost converter is shown in Figure 4. The input voltage is 1.0 V. It can be seen that the output voltage is very sensitive to changes in the duty cycle ($d > 0.8$). This leads the instability in the output voltage. Therefore, the duty cycle should be smaller than 0.8. It means that the maximum output voltage should be smaller than five times the input voltage. In the DC/DC boost converter, the inductance and capacitance can be obtained from:

$$L = \frac{V_i d}{f \Delta I_i} \tag{6}$$

$$C = \frac{I_o d}{f \Delta V_o} \tag{7}$$

where,
L : is the inductance,
C : is the capacitance,
f : is the switching frequency,
ΔI_i : is the peak-to-peak inductor ripple current,
ΔV_o : is the peak-to-peak capacitor ripple voltage,
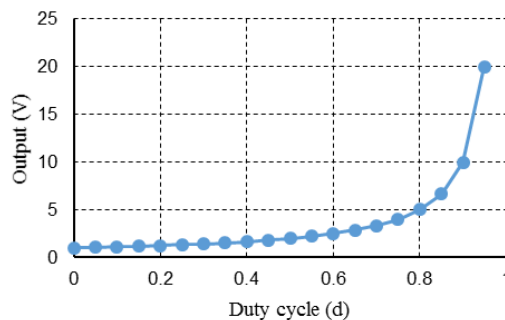I_o : is the average output current.

Figure 4. Relationship between duty cycle and output voltage

2.3. Proposed energy harvesting system

      The output voltage of MFC is often low. It is about 0.33 V. This voltage cannot apply to electronic devices that require at least 3.3 V in practice. The energy harvesting systems from MFC, such as a capacitor and charge pump, cannot supply enough high voltage for applications. Besides, it is also clear that the output voltage of the DC/DC boost converter is limited by the duty cycle of semiconductor switches because the high duty cycle will cause instability in the output voltage. The combination between the charge pump and DC/DC boost converter can solve this problem. The charge pump harvests the energy from MFC and stores it in a supercapacitor. Then, the DC/DC boost converter increases the voltage to the desired level. However, this system is complicated. It requires knowledge of both the charge pump and DC/DC boost converter. Therefore, this paper proposes an energy harvesting system from MFCs in the wastewater treatment system that consists of two DC/DC boost converters. The electrical load is resistive. The arrangement of the energy harvesting system is shown in Figure 5. Two converters have the same structure. However, their function is different. The first DC/DC converter is used to harvest energy from MFC and boosts voltage. The harvesting energy is stored in a supercapacitor. Then, the second DC/DC converter boosts this voltage to a higher voltage level what can apply to electronic devices.

      This energy harvesting system has the advantages such as simple structure, uncomplicated design and control, low cost, and stable operation. As mentioned before, two DC/DC converters have the same structure. To understand this system, the researchers only need the information on the DC/DC boost converter and its control. Compared to the energy harvesting system that combines the charge pump and the DC/DC boost

converter, this system is simpler. Moreover, the system's capacity can be easily increased by connecting the first DC/DC converters in parallel.

The detailed operating principle of the energy harvesting system is as follows;

- First DC/DC converter: Assuming that the supercapacitor C_1 is fully charged at the initial time. If MOSFET M_1 is on, the inductor L_1 is charged energy by MFC. The current i_1 increases gradually, and the MFC voltage is decreased. When the MFC voltage reaches a low threshold V_{LTh1}, MOSFET M_1 is off. Then, the inductor L_1 discharges its energy through diode D_1 to charge the supercapacitor C_1. When the MFC voltage recovers to a high threshold V_{HTh1}, MOSFET M_1 is on again. This process is repeated in the next period. The supercapacitor C_1 stores energy from MFC and reduces the ripple in the output voltage of the first DC/DC converter.

- Second DC/DC converter: The second DC/DC converter is operated by closing the MOSFET M_3 when the supercapacitor voltage v_{C1} reaches a high threshold V_{HTh2}. If MOSFET M_2 is on, the inductor L_2 is charged energy from the supercapacitor C_1, and the capacitor C_2 discharges its energy to the electrical load. The current i_2 increases gradually, and the supercapacitor voltage is decreased. If MOSFET M_2 is off, the inductor L_2 discharges its energy through diode D_2 to the electrical load and charges the capacitor C_2. This process is repeated in the next cycle. The second DC/DC converter is off by opening the MOSFET M_3 when the supercapacitor voltage reaches a low threshold V_{LTh2}.
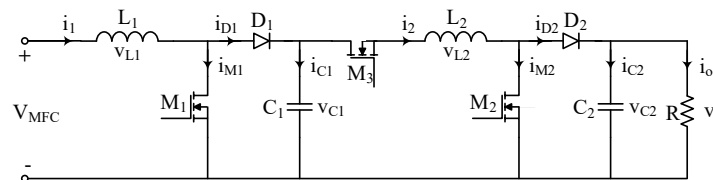

Figure 5. Energy harvesting system of MFC

3. EXPERIMENTAL RESULTS AND DISCUSSION

The configuration of the experimental setup is shown in Figure 6. It is established from the circuit diagram in Figure 5. The MFC is simulated by a DC voltage source. In practice, when an electrical load is connected to the MFC, the MFC voltage will be decreased. Then, if the electrical load is removed, the MFC voltage will be restored. In the first experimental model, one first DC/DC converter is connected to one second DC/DC converter based on the structure in Figure 5. The MFC voltage is controlled from 300 to 360 mV as shown in Figure 7 (orange curve) [2], [21], [23], [24]. If the MFC voltage reaches a low threshold of 300 mV, the MOSFET M_1 is off, and the inductor L_1 discharges its energy through a diode to charge a supercapacitor. The voltage across the supercapacitor, v_{C1}, is $v_{MFC} + v_{L1}$. At the steady-state time, this voltage is about 1.0 V as illustrated in Figure 8, and it depends on the on time of MOSFET M_1. In the MFC, the voltage and power density depend on the bacterial activity. In other words, the on time and off time of MOSFET M_1 are determined by the bacterial activity. As soon as the inductor L_1 discharges its energy, the current through it is decreased. Moreover, this current is also the MFC current. Thus, the MFC voltage increases. This is similar to the restoration of the bacterial community leading to the increase in electrons and protons. Once the MFC voltage reaches the high threshold of 360 mV, the MOSFET M_1 is on. The inductor L_1 is charged energy from MFC, and the MFC current increases. Therefore, the MFC voltage will be decreased gradually low threshold of 300 mV. Then, the discharging process of the inductor L_1 is repeated in each cycle. In Figure 7, the blue curve is the gating signal for the MOSFET M_1 what depends on the MFC voltage. The duration to charge the supercapacitor from 0 V to 1.0 V is about 48 minutes.
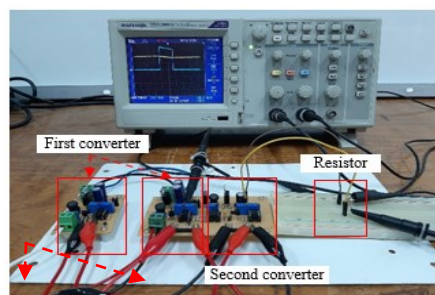

Figure 6. Configuration of the experimental setup

Model of an intelligent energy harvesting system from microbial fuel cells ... (Ngoc-Thinh Quach)
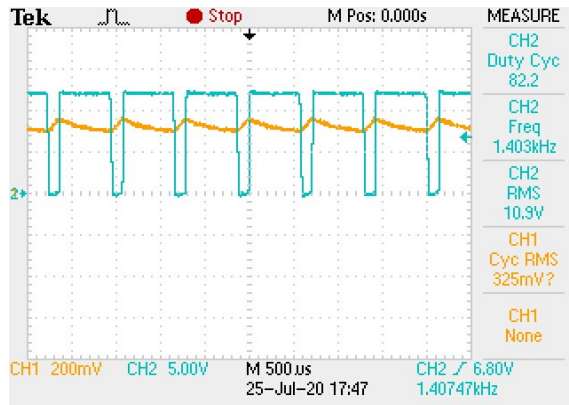
Figure 7. MFC voltage and MOSFET gating signal

Figure 8. Supercapacitor voltage

The operation of the second DC/DC converter is based on the supercapacitor voltage. When the supercapacitor voltage reaches the high threshold of 1.0 V, the MOSFET M_3 is on. The output voltage of the second DC/DC converter, v_o, depends on the duty cycle of the MOSFET M_2 what is a constant value. Thus, the output voltage, v_o, is proportional to the supercapacitor voltage as shown in Figure 9. If the supercapacitor voltage is 1.0 V, the output voltage will achieve the maximum value of 3.3 V that is connected to a resistor of 1 kΩ. Therefore, the maximum output current will be 3.3 mA. The corresponding duty cycle is about 0.26 as shown in Figure 10. When the second DC/DC converter operates, the supercapacitor voltage is decreased. Consequently, the output voltage will also be decreased at the same time.

As soon as the supercapacitor voltage reaches 0.9 V what is corresponding to the output voltage of 3.0 V, the MOSFET M_3 will be off. The supercapacitor is charged energy from the MFC, and its voltage increases again. The duration to charge the supercapacitor from 0.9 V to 1.0 V is about 8 minutes, and the discharging duration is about 44 seconds. The MFC output power is about 3.0 mW, similar to an MFC in practice [23]. The average load power is approximately 10.89 mW.
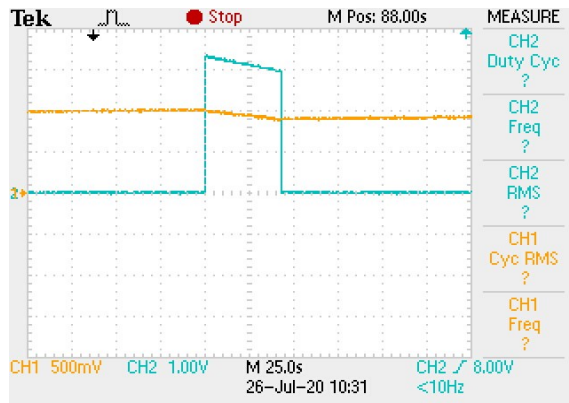

Figure 9. Supercapacitor voltage and
output voltage

Figure 10. Gating signal of second DC/DC
converter

In the next experimental setups, the first DC/DC converters are connected in parallel, or the load is changed to verify the discharging duration, charging duration, and capacity of the MFC system. The operating results of the energy harvesting system in these cases are shown in Table 1. Table 1 shows that the combination of many first DC/DC converters in parallel can increase the capacity of the MFC system. This is important because the higher MFC output power cannot be easily obtained by increasing the sizing of MFC [6], [7]. Depending on the electrical load or number of first DC/DC converters, the discharging duration and charging duration will be different. For example, the output voltages v_{C1} and v_o in the case of three first DC/DC converters connected in parallel are shown in Figure 11.

Table 1. Operating results

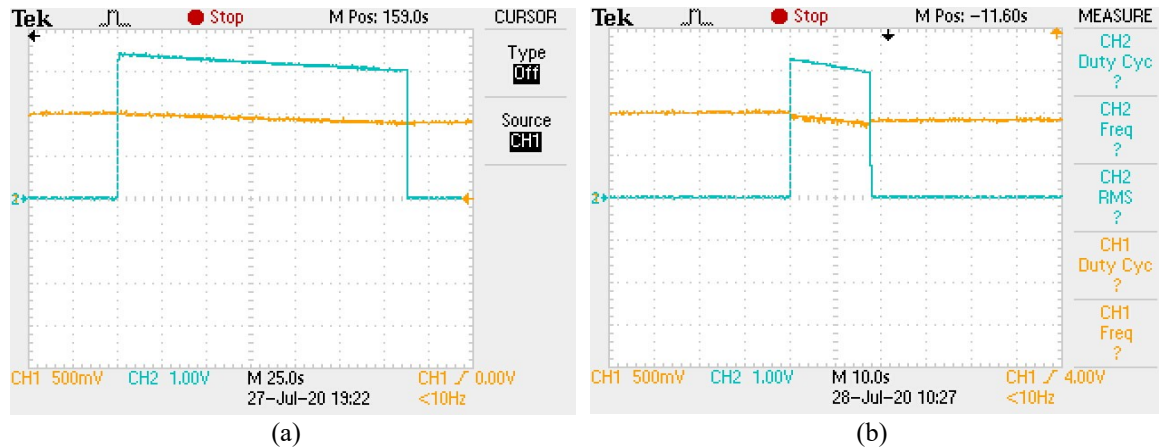| Resistor (Ω)	No. of first DC/DC converters	Discharging time (s)	Charging time (s)
1000	1	45	500
	2	97	554
	3	162	530
180.8	1	4	234
	2	11	452
	3	18	450

Figure 11. Three first DC/DC converters connected in parallel; (a) R = 1000 Ω and (b) R = 180.8 Ω

With two different load levels, the voltages v_{C1} and v_o are still in their ranges as designed before. Thus, the output power of the MFC system is stable. As a result, the MFC can be applied to electronic devices in practice [24], [25]. For example, the sediment-microbial fuel cell can be achieved the maximum output power of 2.5 mW what can use for the PowWow system with the power of 240 μW [25]. In this experimental setup, the output power will be 60.23 mW if three first DC/DC converters are connected in parallel. The discharging duration will be 18 s (Table 1) what is enough for transferring a signal packet [25]. The output power supplied from the supercapacitors in the first DC/DC converter may be intermittent if the power load is higher than that of the MFC system.

Besides, by using a double capacity of supercapacitor at the first DC/DC converter, the discharging duration is also similar to two first DC/DC converters connected in parallel. However, the charging duration is double times. It means that the structure of the MFC harvesting energy system will depend on the duration of collecting and sending a signal packet.

From the results, it is demonstrated that the proposed energy harvesting system from MFCs can increase the low voltage of MFCs (0.33 V) to higher voltage (3.3 V) what is similar to the system consisting of the charge pump and DC/DC boost converter [15]. However, the structure and operation of a system with two DC/DC converters connected in a cascade are simpler. Moreover, the efficiency of the DC/DC converter is higher than that of the charge pump. Besides, the energy harvesting system's capacity can be increased easily by connecting the first DC/DC converter in parallel.

4. CONCLUSION

This paper has presented a method to harvest energy from the MFCs in the wastewater treatment process using two DC/DC converters connected in a cascade. The first DC/DC converter has two functions: 1) harvesting the energy from MFC; 2) boosting the MFC voltage (0.33 V) to a higher value (1.0 V). The second DC/DC converter is used to increase this voltage to a higher voltage level (3.3 V) that is suitable for electronic devices. This operating principle is to limit the duty cycle of the second DC/DC converter to achieve a stable operation. The intelligent harvesting energy system can harvest the low power from MFC and stores it in the supercapacitor of the first DC/DC converter. Then, this supercapacitor discharges the energy with high density through the second DC/DC converter to the electrical load. By connecting many first DC/DC converters in parallel or many supercapacitors in the first DC/DC converter in parallel, the output power of the MFC system can be increased to the level that can use in practice. In summary, the proposed energy harvesting system with simple structure and control can obtain the voltage, current, and power demands of the load. In future work, this system will test on the low power sensor such as a temperature sensor.

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